NSTX-U

NSTX-U is sponsored by the
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Fusion Energy Sciences

Modes in the GAE 2nd Harmonic Frequency Band

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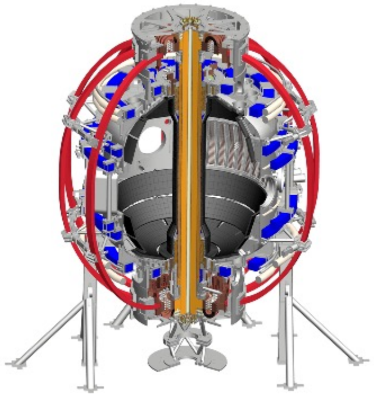
EP Meeting
PPPL, Princeton, New Jersey
Sept. 14, 2022

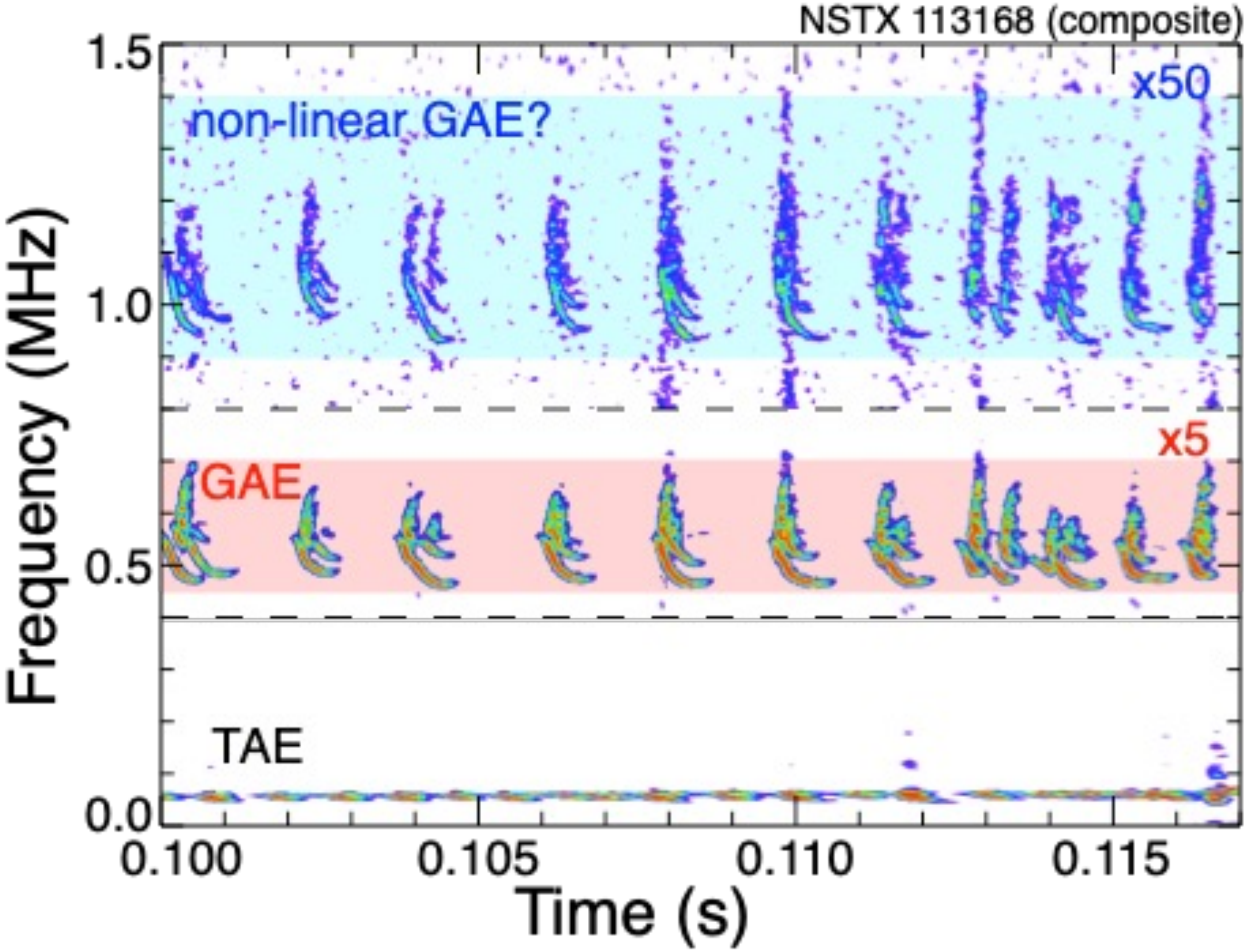


PPPL

Modes at the second harmonic of GAE are common in NSTX

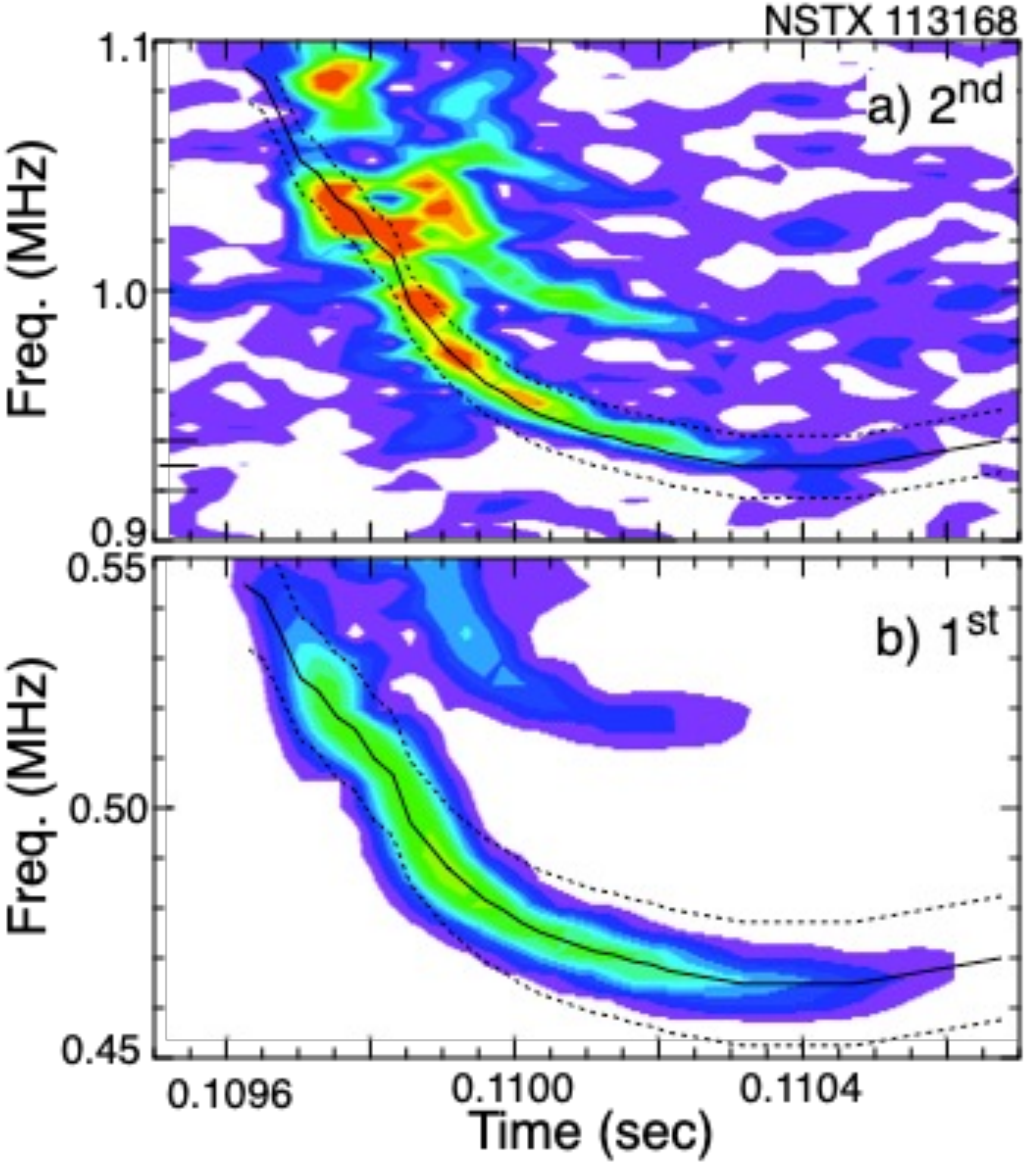
- In this example, both 1st and 2nd harmonic GAE bursts show chirping consistent with formation of holes and clumps in the fast ion distribution

- 2nd harmonic GAE could be from:
    - non-linear terms in GAE dispersion equations => 3-wave coupling
    - independent weakly damped modes triggered by displaced fast ions
    - non-linearly driven GAE, off their natural frequency?
- Most observations support wave-physics non-linearities.
- Further, the data suggests in some cases that weakly damped modes were transiently excited.



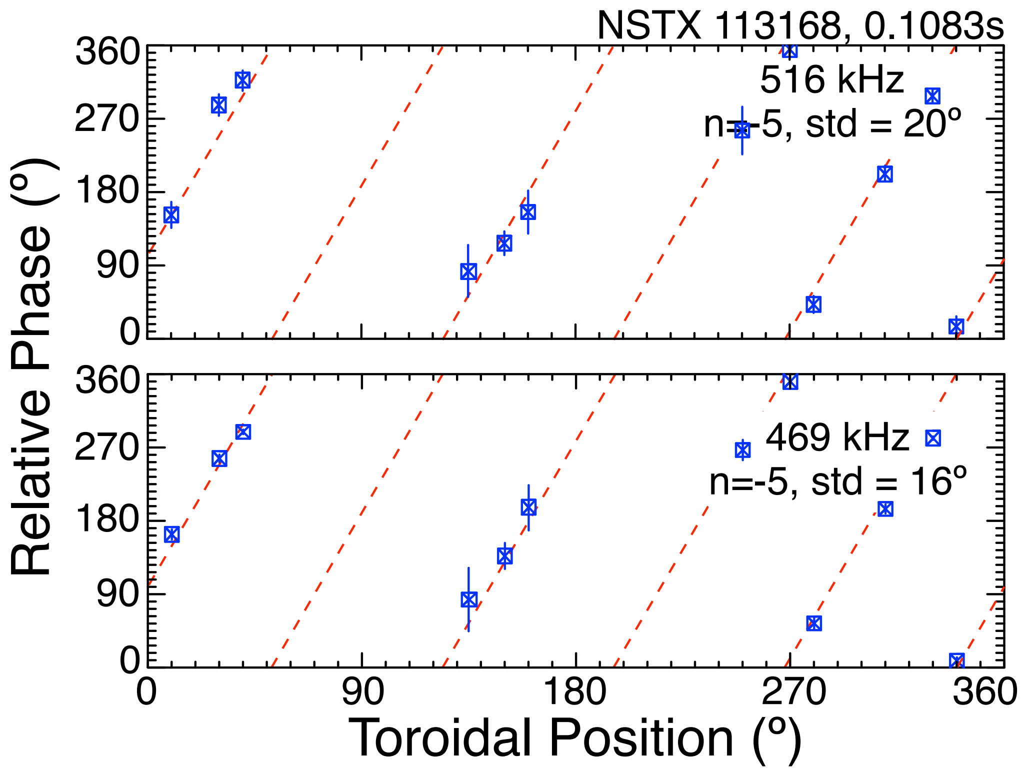
We begin with the GAE burst at 0.11s from previous slide, and its 2nd harmonic components

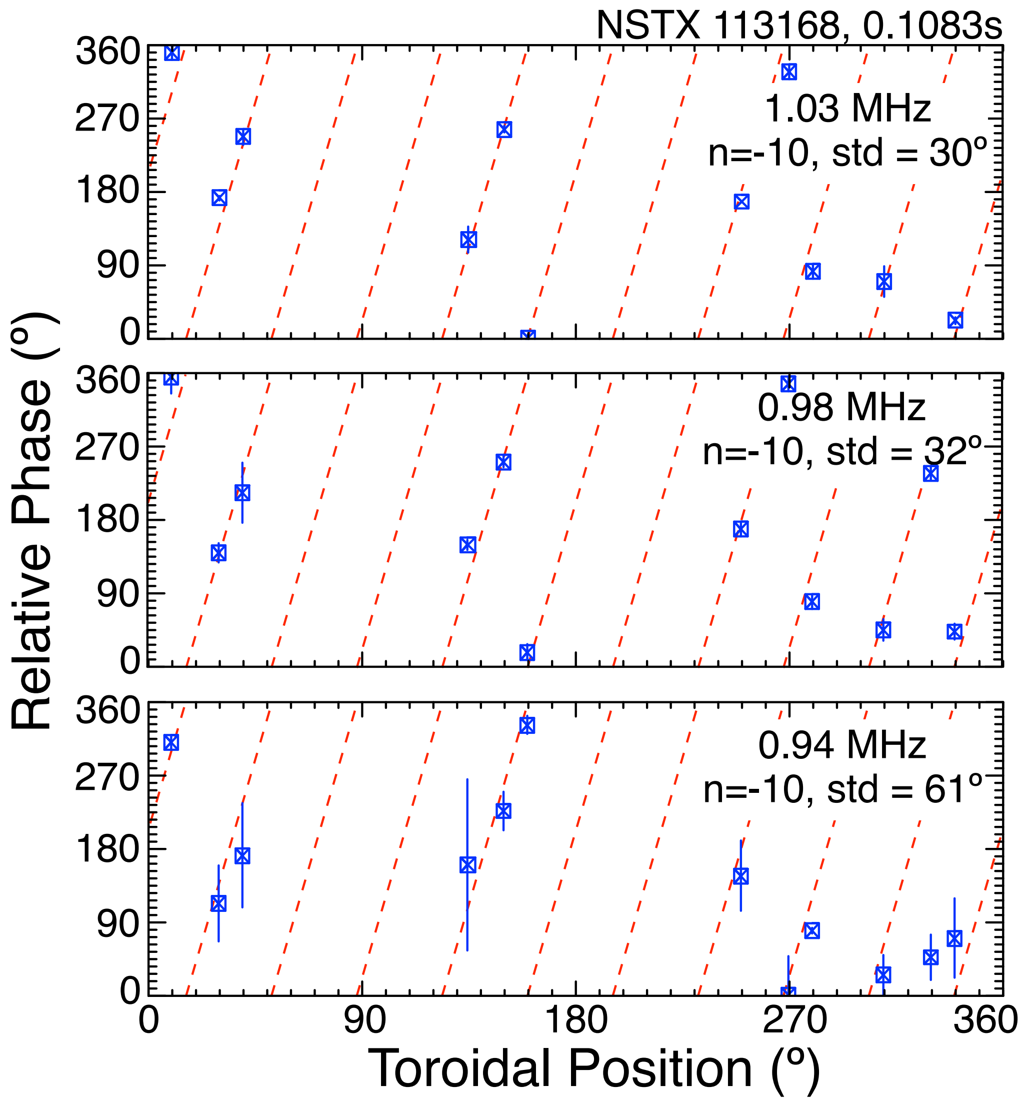
- A non-linear 2nd harmonic perturbations' amplitude should scale quadratically with the fundamental amplitude.
  - The frequencies should be the sum of frequencies of the fundamental mode
  - the mode number should be the sum of the fundamental mode numbers
- The amplitude scaling is found by tracking the mode frequency and calculating the RMS amplitude *vs.* time
  - solid line tracks mode center frequency.
  - short dashed lines indicate frequency range for RMS calculation.
- We compare the phase between the non-linear perturbation and 2nd harmonic mode.



In this example the 2nd harmonic frequencies and mode numbers are consistent with non-linear 3-wave coupling

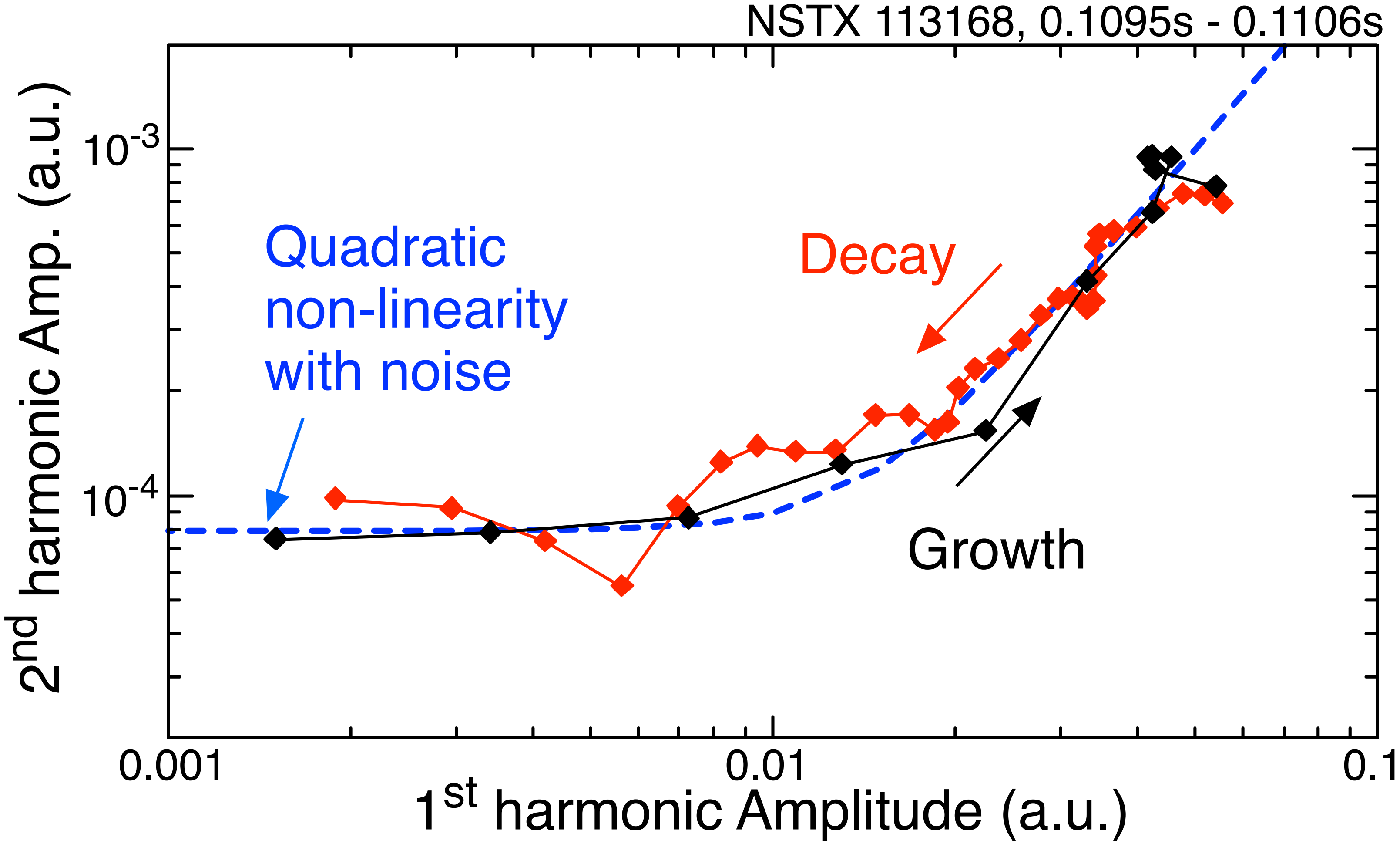
- Fundamental modes were n = -5 and 2nd harmonic modes were n = -10.





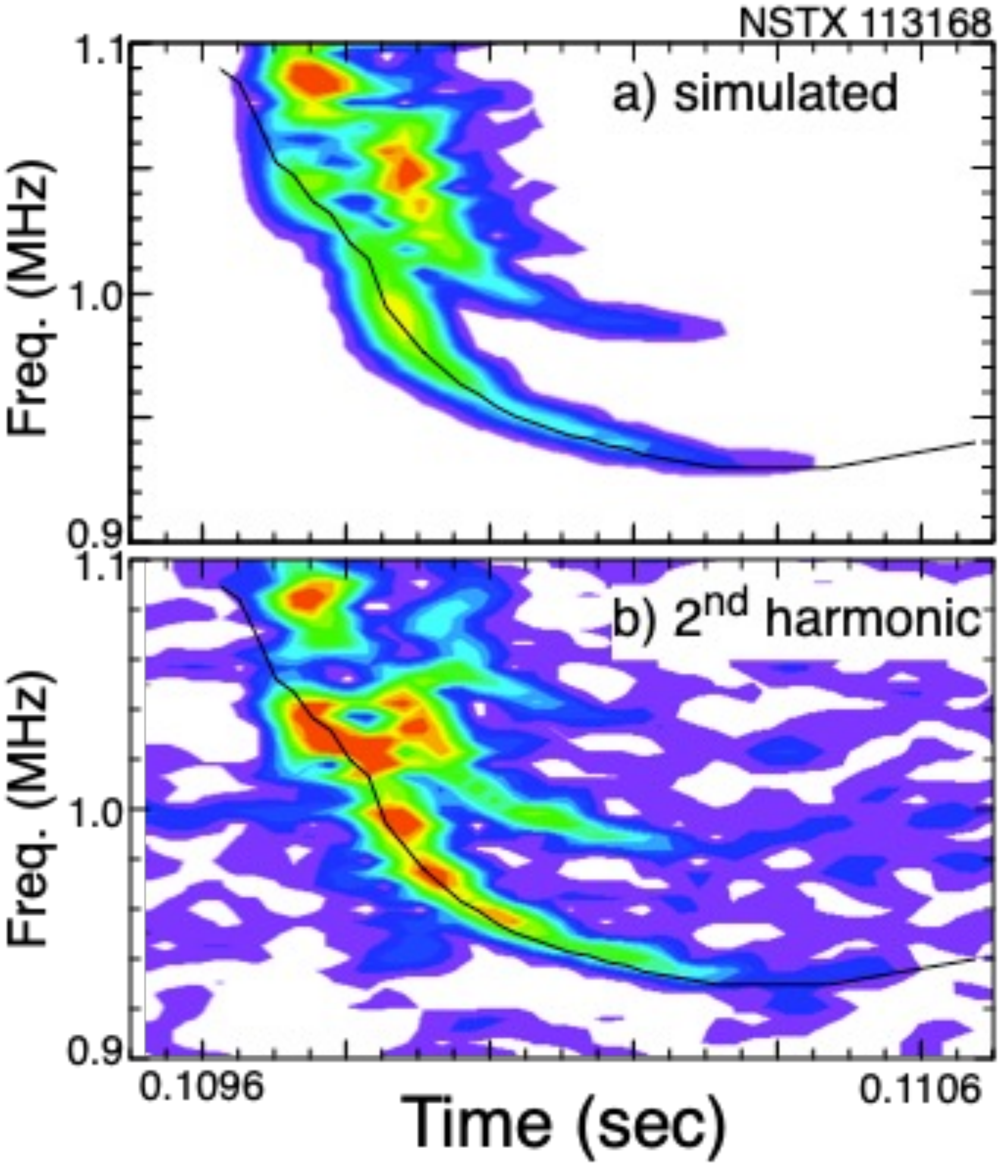
2nd Harmonic Mode amplitude tracks fundamental

- The time-dependent RMS mode amplitudes are calculated for a fundamental and 2nd harmonic GAE mode.
- The second harmonic amplitude is plotted vs. the first harmonic amplitude on a log-log scale.
- The weak 2nd harmonic mode has low signal-to-noise at the beginning and end of the pulse,
    - The blue dashed curve shows the expected trajectory of the 2nd harmonic amplitude including noise added in quadrature.



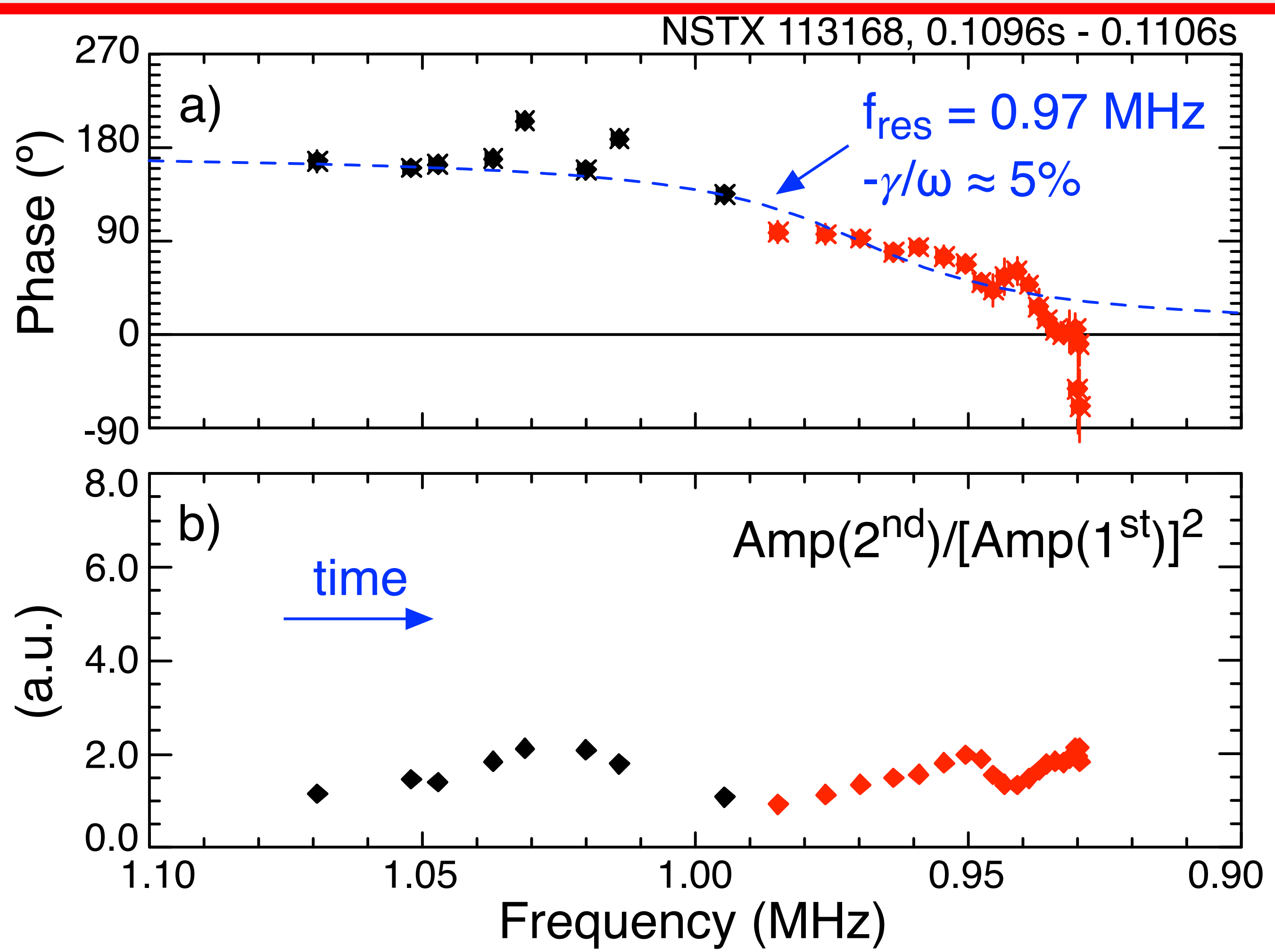
We simulate the 2nd harmonic perturbations using the fundamental modes

- The raw data is filtered to preserve only the fundamental mode.
- That is squared, to simulate a quadratic, non-linear perturbation at the 2nd harmonic.
- The spectrograms of the simulated 2nd harmonic perturbation and the measured 2nd harmonic fluctuations are compared at right.
- There is a strong qualitative agreement between the two spectrograms,
  - There are some subtle differences in the relative mode amplitudes and in the amplitude evolutions,
  - although noise and potential differences in radial mode structure could account for some of this.



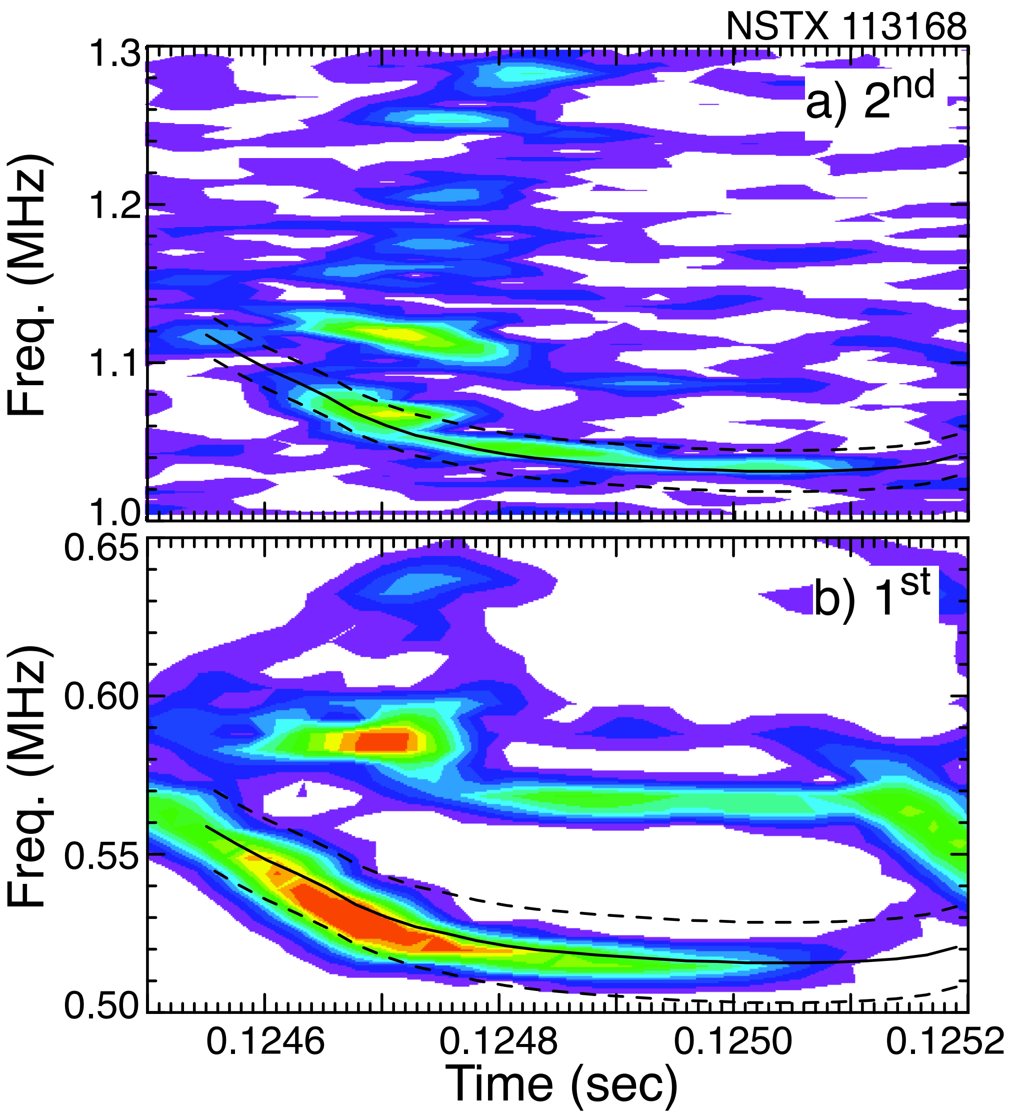
The relative phase can be calculated between the simulated and measured 2nd harmonic modes

- The relative phase for the mode indicated by the black curve is shown at right.
  - The dashed blue line shows the (adiabatic) phase *vs*. frequency for a driven oscillator with damping.
- The 2nd harmonic amplitude is normalized to the square of the fundamental and shown in b),
  - The nearly constant ratio is consistent with a weak effect of the plasma on the 2nd harmonic perturbations.

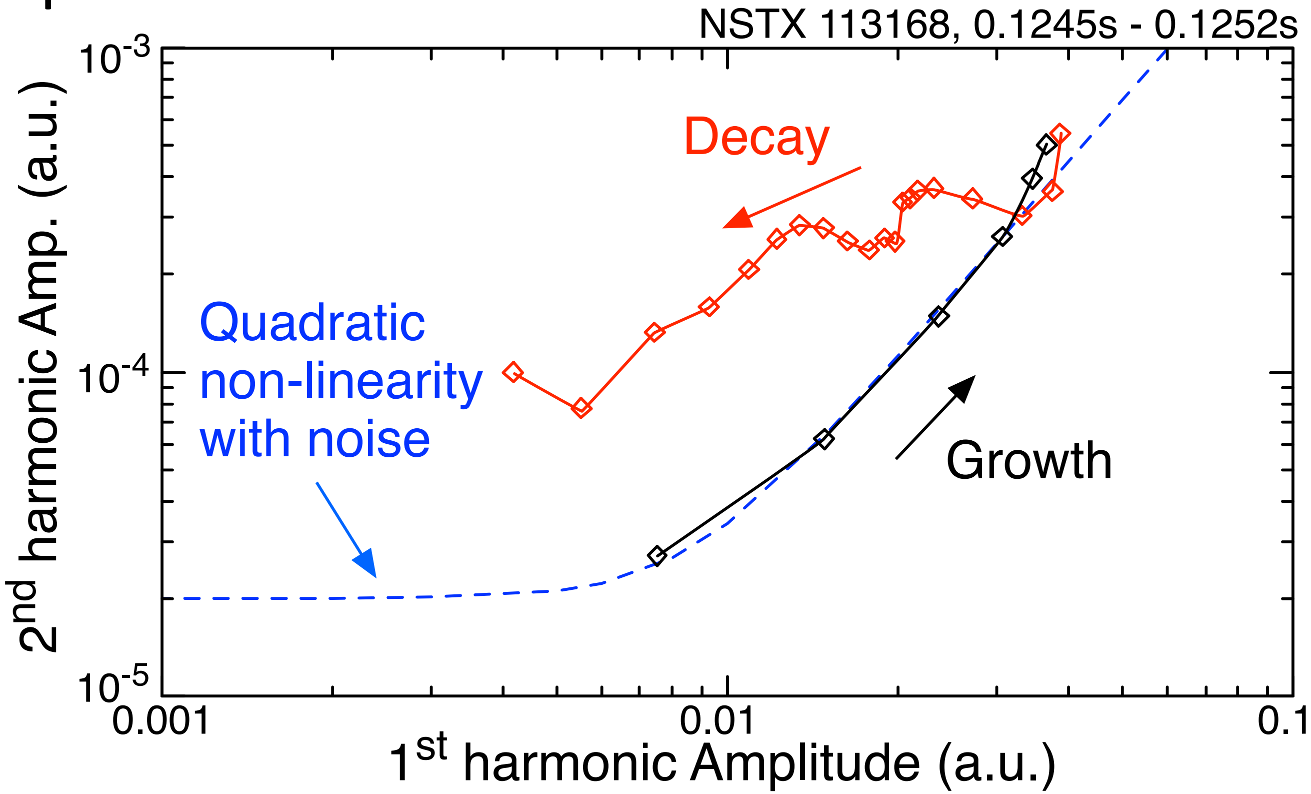


- Expected phase shift is ≤180º for drive frequency greater than resonant frequency, 90º at resonance and ≈0º for drive frequency less than resonant frequency.

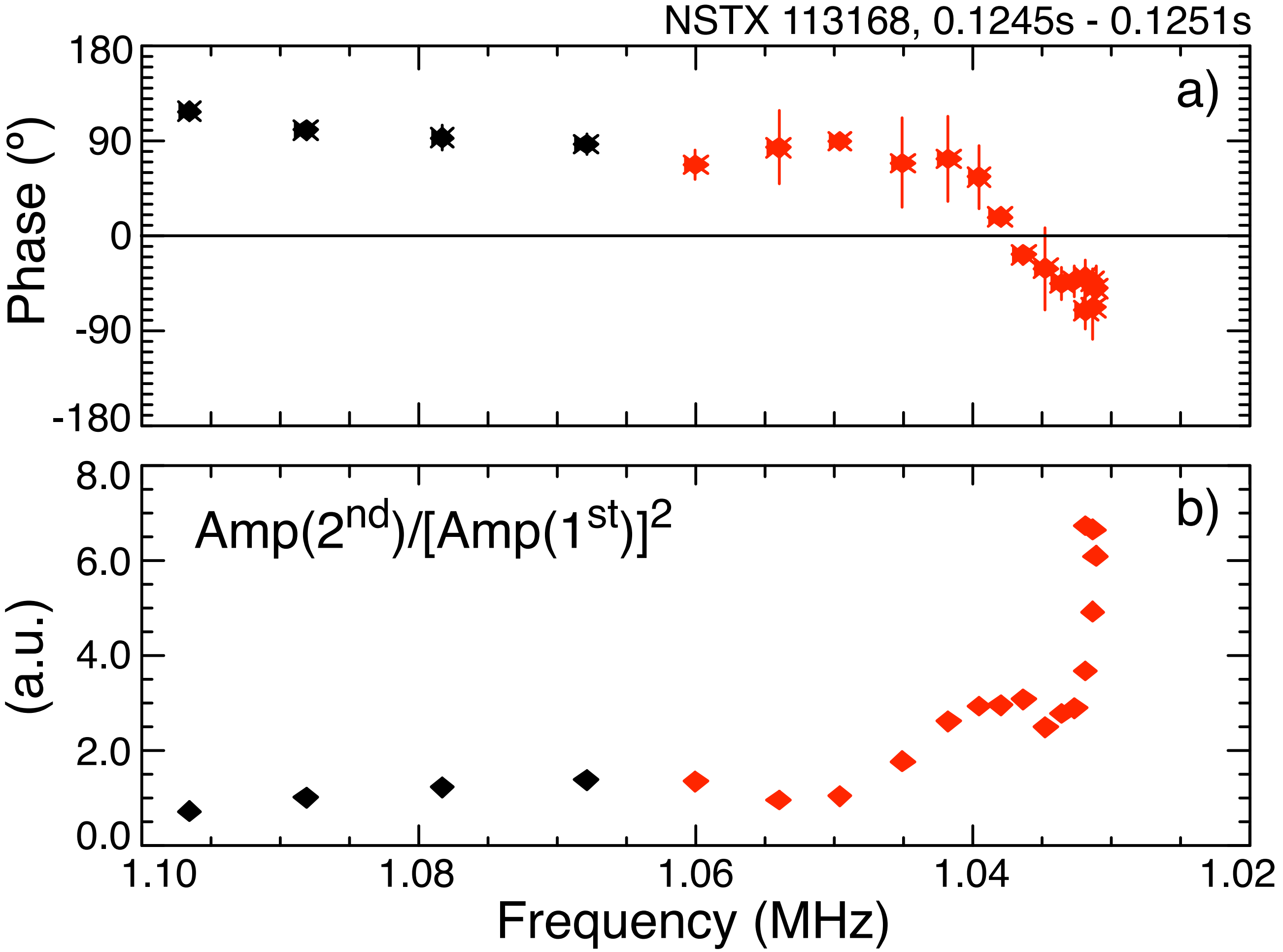
Other cases provide more evidence of the independence of the 2nd harmonic GAE



- Mode decay shows hystereris, suggesting this is weak coupling to independent modes?
- This example is taken from same shot, but about 15 ms later – nearly identical plasma parameters.



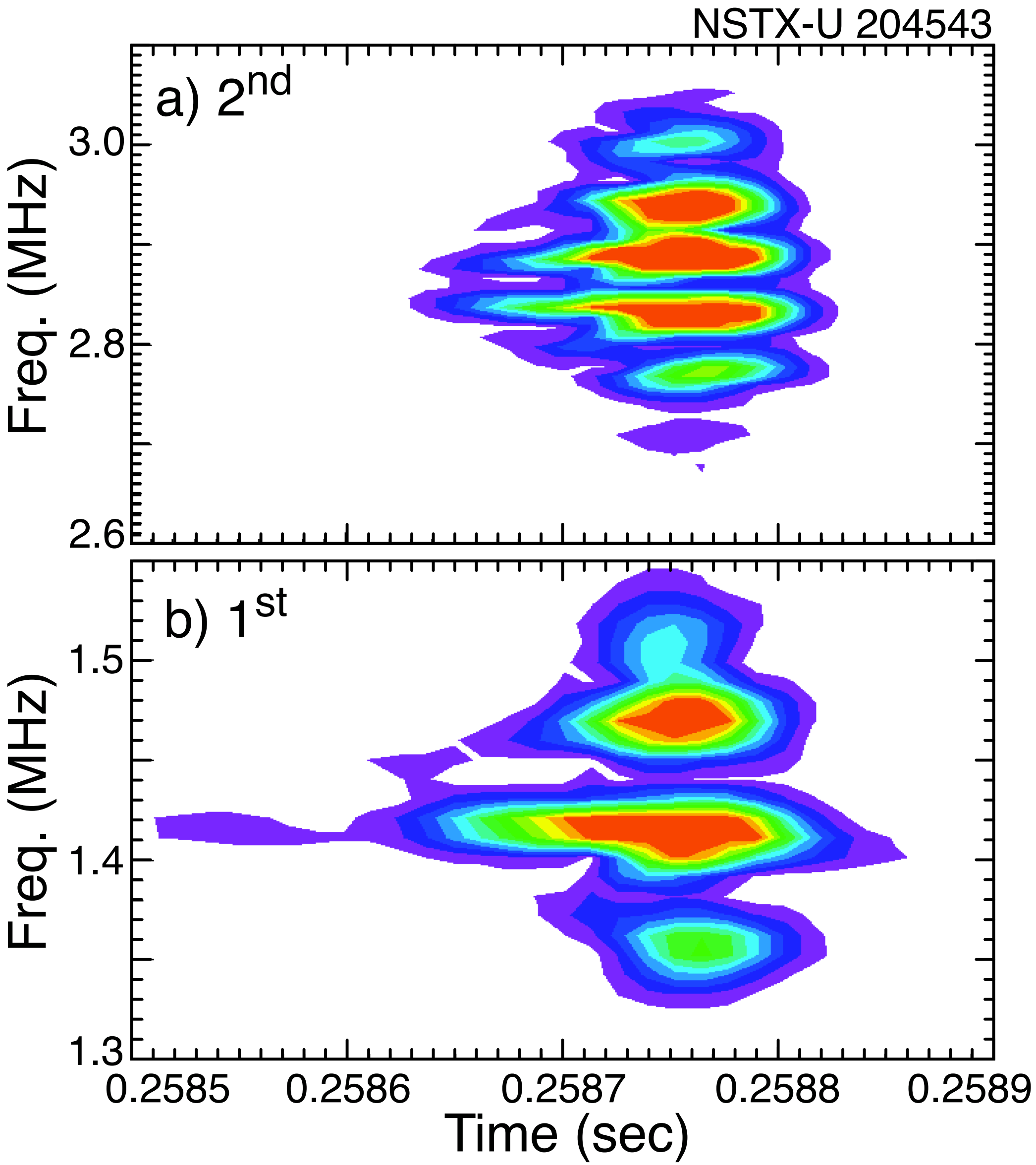
The relative phase differs in this case



- The relative phase shift suggests drive frequency is near resonance frequency?
  - While frequency chirps down 60 kHz?
- Could damping be much higher in this shot, broadening resonance?

- Expected phase shift is ≤180º for drive frequency greater than resonant frequency, 90º at resonance and ≈0º for drive frequency less than resonant frequency.

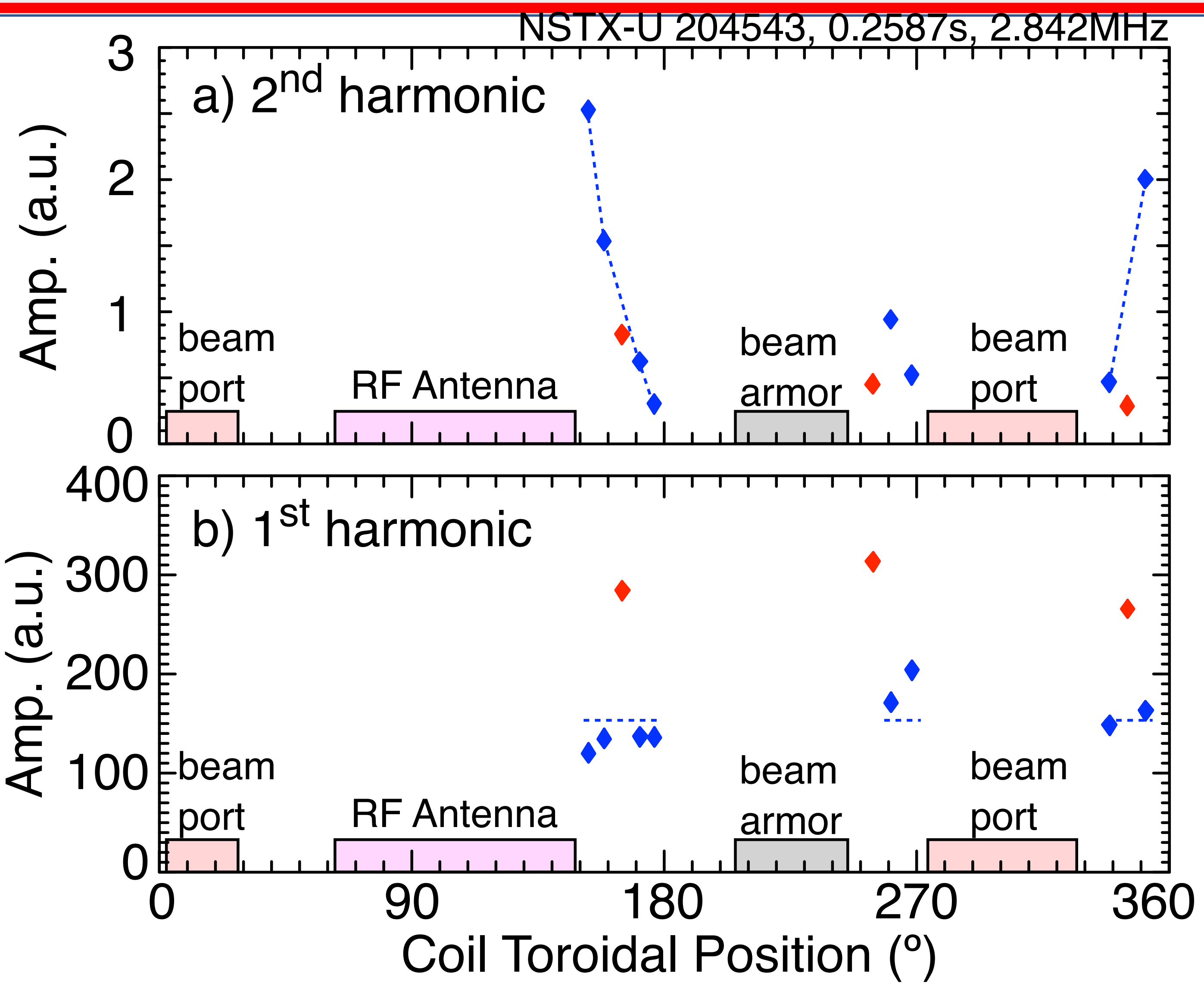
GAE bursts in higher field plasmas are shorter, less likely to chirp



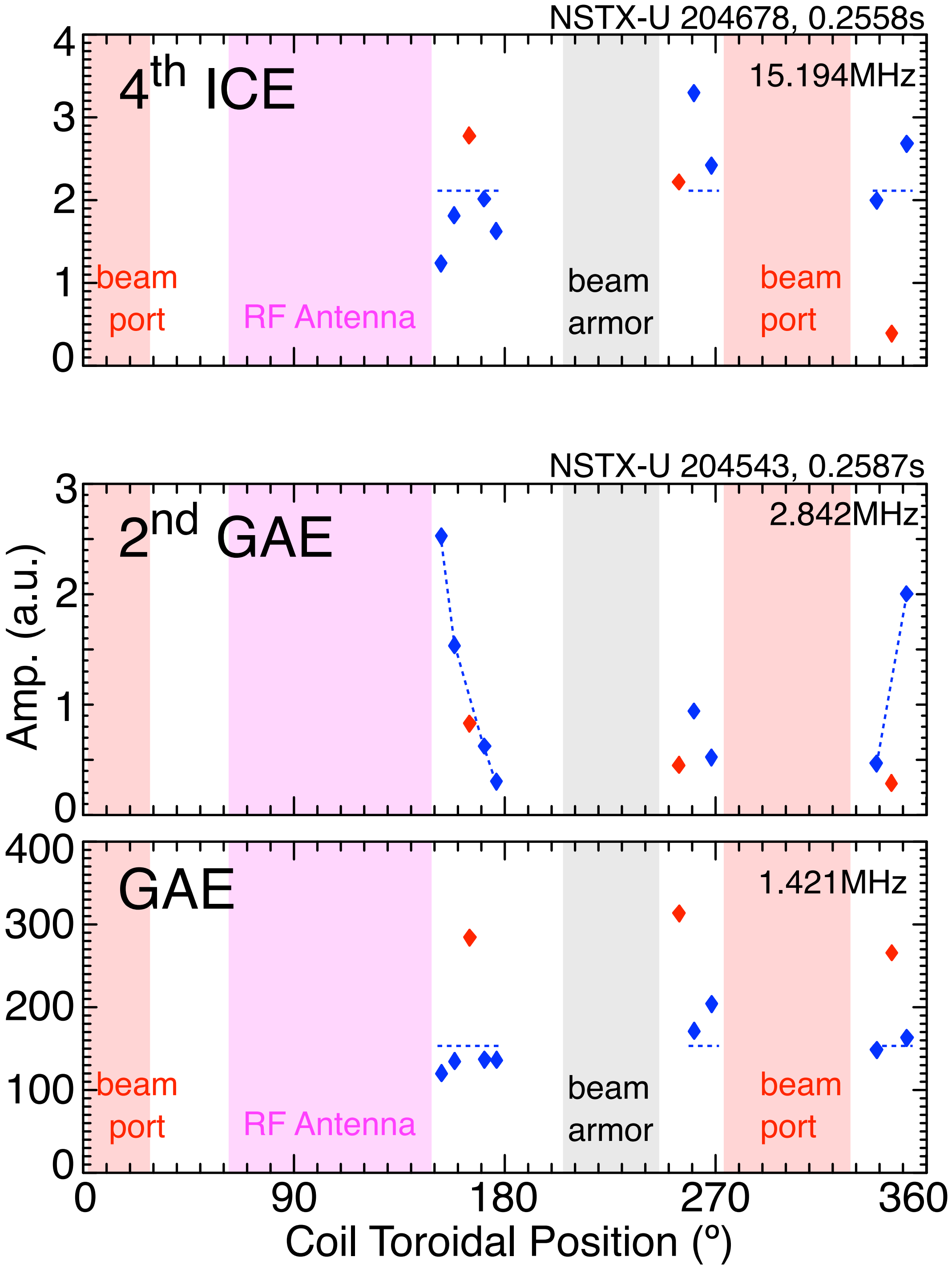
- A typical GAE burst in a 5.9 kG plasma
  - (previous example was 2.7kG).
- Fundamental mode numbers are n = 9, 10, 11.
- 2nd harmonics should range from n = 18 to 22.
- There might be some small frequency chirping, but by any measure it's much less than in low field GAE bursts.

Large toroidal variation in 2nd harmonic amplitude

- Data suggests 2nd harmonic mode is localized in front of RF antenna.
- Could the strong localization be correlated with the shorter wavelengths at higher field?
- Not much chance of adding sensors there.
- Plans are to add sensors in 30º to 60º span.

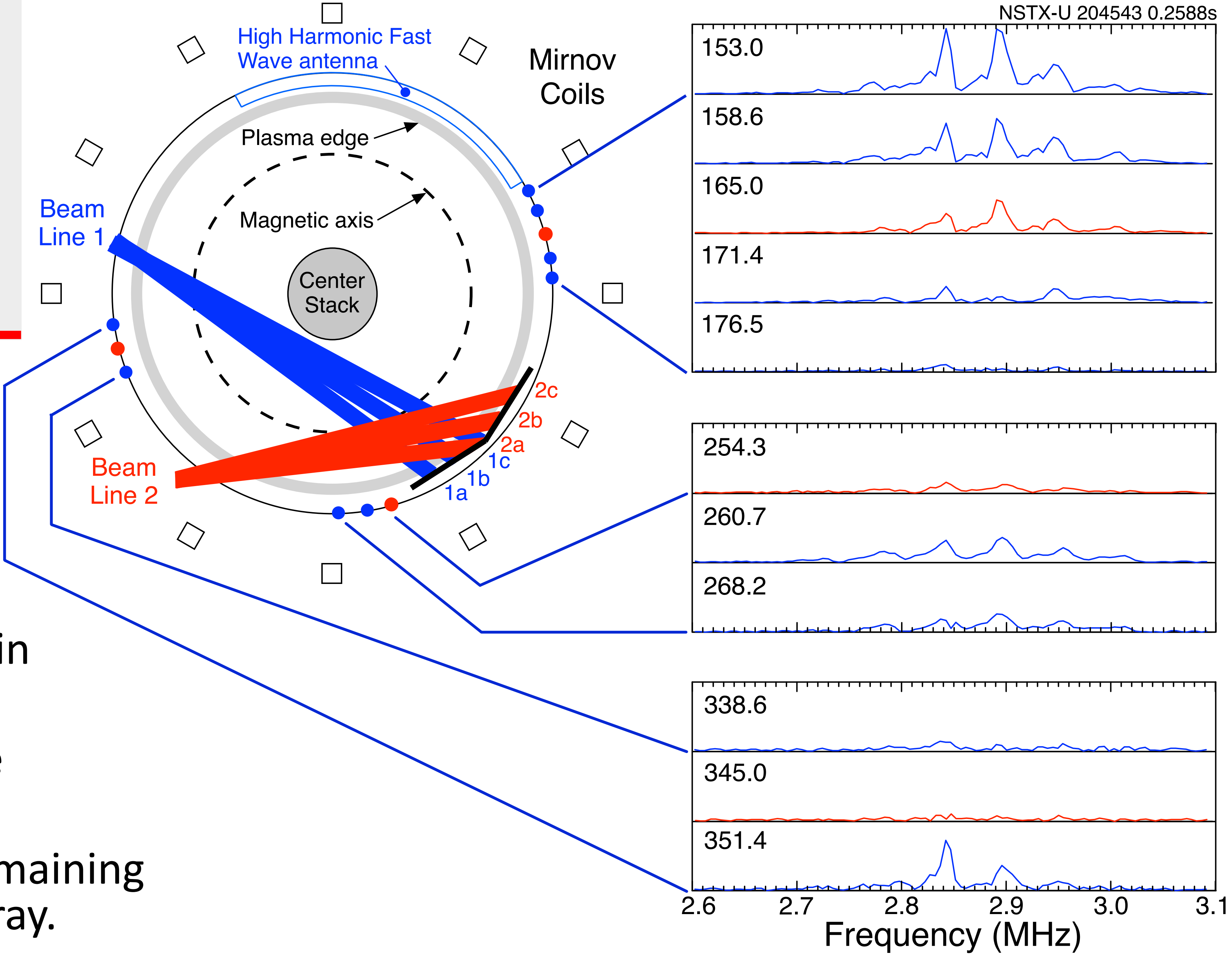


Not a bandwidth issue for magnetic sensors



- Not much besides ICE inhabits the frequency range above 4 MHz in NSTX-U.
- The 4th harmonic ICE at 15 MHz is roughly toroidally symmetric,
  - it was also possible to measure the mode number.
- Generally, other ICE harmonics are also toroidally symmetric.
- ICE is also long wavelength with $1 \leq |n| \leq 4$

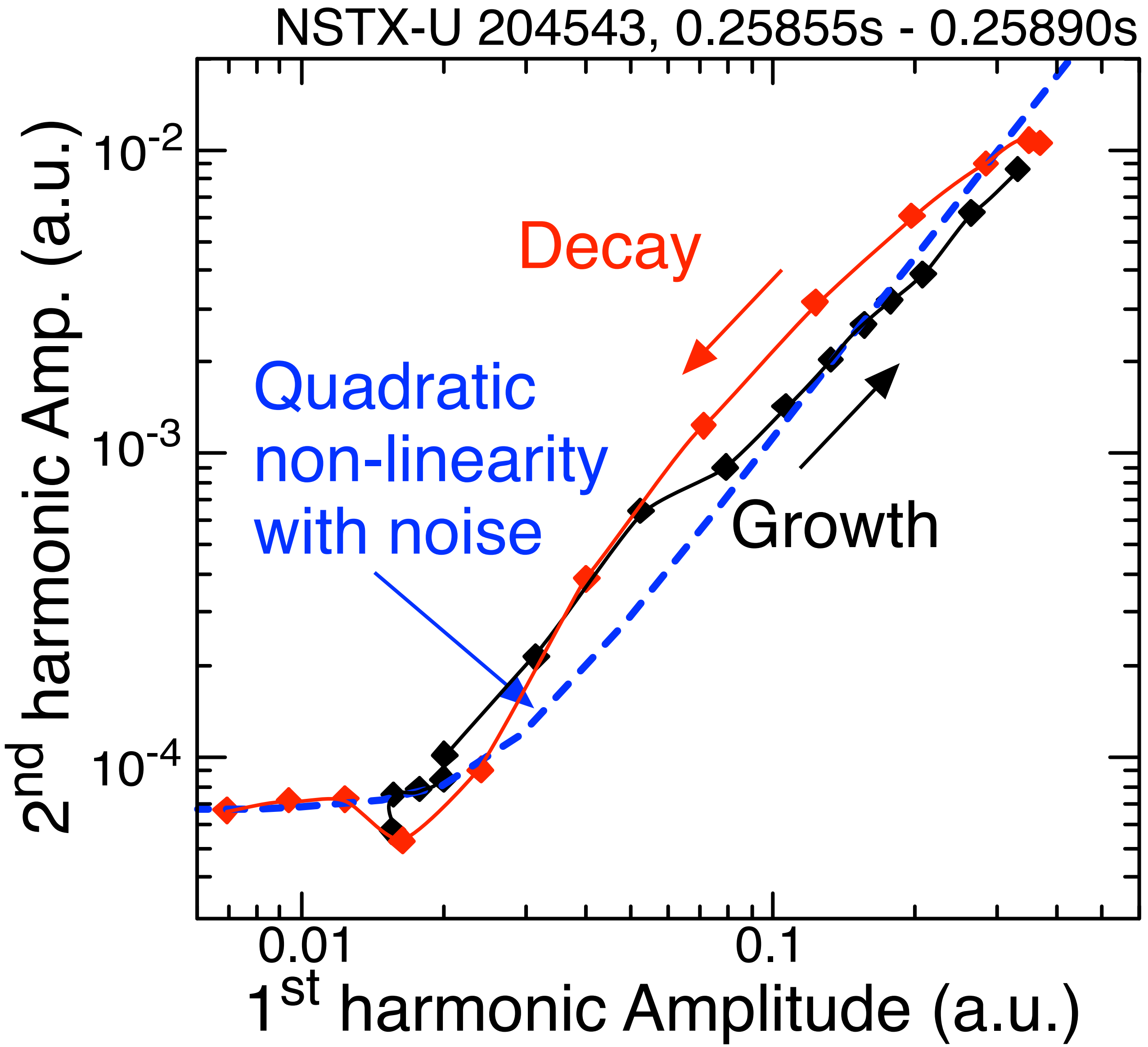
Spectra show toroidal Amplitude of 2nd harmonic GAE



- Good signal-to-noise in spectra.
- All modes show some localization.
- Only limited space remaining to expand toroidal array.

Mode amplitudes approximately consistent with quadratic non-linearity

- Roughly quadratic ratio over two orders of magnitude
  - relatively lower noise in this frequency range.
- Scaling is same in strong and weak areas.



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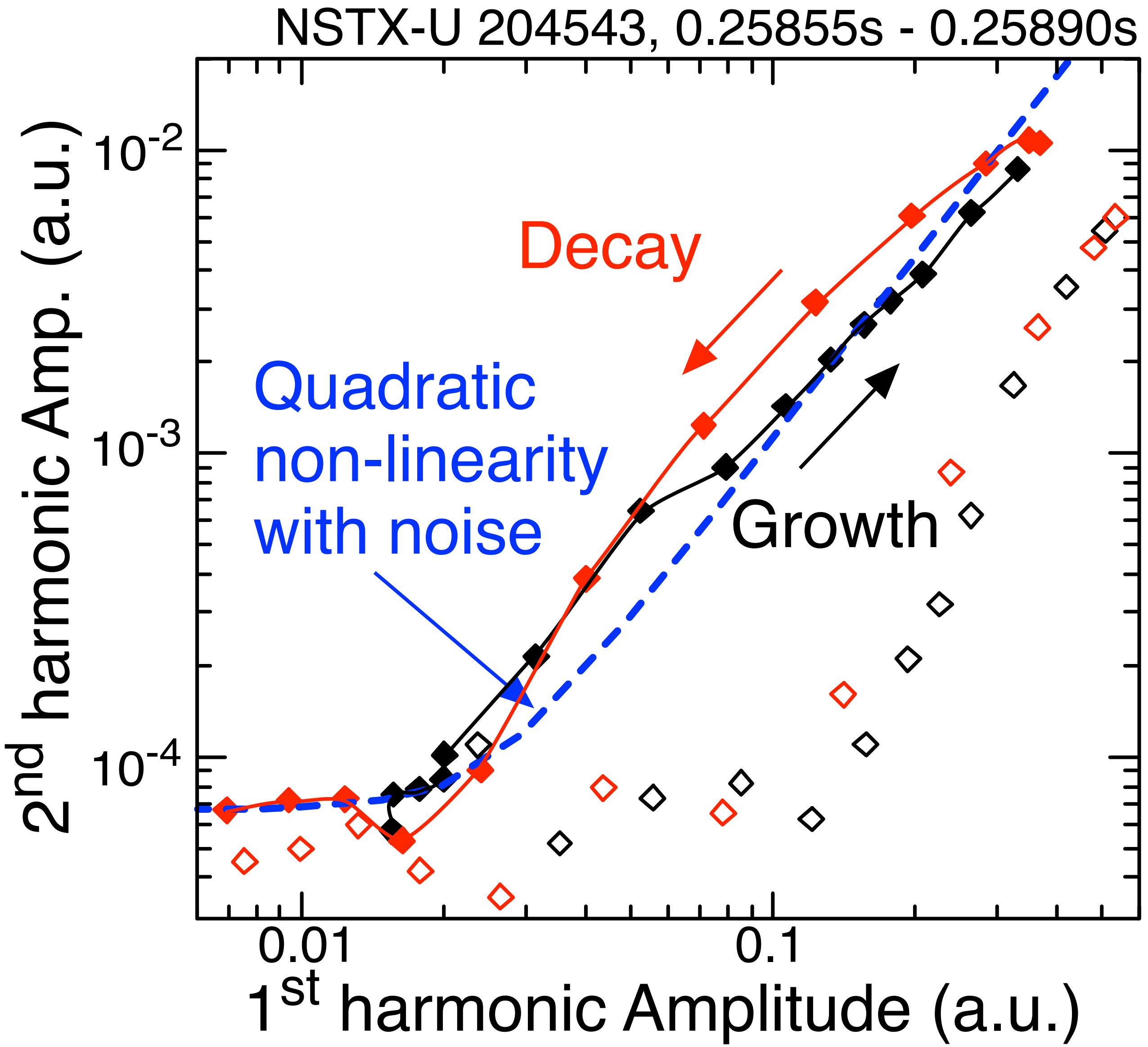
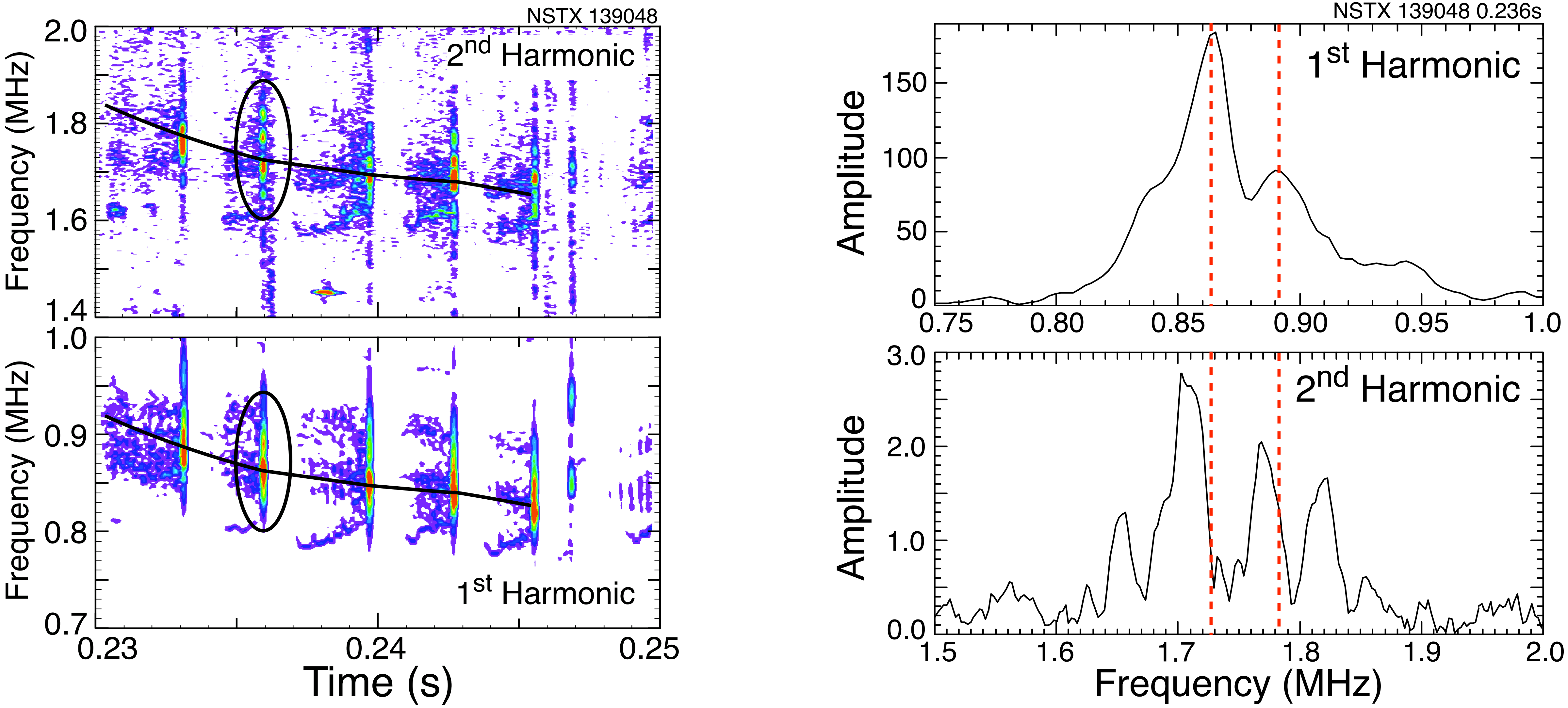


Frequencies don't always satisfy 3-wave coupling rule

- However, noise from switching Power Amplifier precludes mode analysis of 2nd harmonic.
- This example also doesn't show frequency chirping.



The 2nd harmonic GAE appear to be partially independent

- Amplitude evolution of 1st and 2nd GAE during burst appears to be de-coupled;
  - small caveat is that amplitude measurement is at plasma edge.
  - Possibly could be explained frequency-dependent 2nd harmonic damping term?
- Toroidally localized 2nd harmonic GAE inconsistent with simple non-linear response;
  - toroidal localization of short wavelength Alfvénic modes is something new.
  - Could have important ramifications for the modeling of TAE induced transport in ITER?
- These results suggest that the fundamental GAE are acting like an antenna where the non-linearity creates perturbations at twice the frequency and half the wavelength
  - not as much control over frequency as with an an antenna, but wavelength is fixed vs. not well defined,
  - drive is weak, but has the advantage of being where the mode is, the antenna has to deal with fast fall-off,
  - because the excitation isn't from the edge, backing out the antenna drive from the measurement is easier,
  - Similar evidence of non-linearity has previously been seen with TAE.

Future work:

- Work out non-linear terms in the GAE dispersion relation derived from Brazinski 2-fluid;
  - is relative amplitude of harmonics reasonable?
  - can anything be understood from scaling with plasma parameters?
- Would hole-clump model of chirping predict non-linear terms as a result of driving GAE off their natural resonance?
  - Fundamentally, waves transfer energy between kinetic (motion of plasma tied to field lines) and potential (energy stored in perturbed magnetic field geometry).
  - If waves driven off natural frequency, energy must be stored in fast-ion distribution to compensate for lower kinetic energy from slower motion at lower frequencies. This would introduce perturbations at twice the mode frequency.
- Larger collection of data needs to be analyzed.
  - How common are disparate frequencies? Disparate mode numbers?
  - What about hole-clump chirps at higher field? Where are they?
  - "Good" Mirnov data only available from 2016 campaign (SPA noise), which was all done at ≈6kG.